On the Integrated Spectrum of the X-ray Binaries and the Origin of Soft X-ray Emission from the Bulge of M31

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ABSTRACT

Using ROSAT PSPC data, we have performed several tests aimed at understanding the origin of the soft X-ray spectral component detected from the bulge of M31. For the first time, we separated the spectrum of bright point sources in the bulge from the diffuse source located in the same region. We find that a significant soft component in the integrated spectrum of the bulge X-ray emission is spatially correlated with the diffuse source near the core of M31, which is probably a hot interstellar medium or perhaps a population of multiple faint sources. A soft component is not needed to fit the point source spectrum after the diffuse emission is subtracted. The integral spectra of bright point sources, both inside and outside of the M31 bulge, can be fitted with a single power-law of photon index ∼1.3 - 1.5 in the ROSAT band. Our analysis rules out the previous suggestion that all bulge emission in M31 may be generated by X-ray binaries (Irwin & Bregman, 1999).

Subject headings: binaries: close — galaxies: individual (M31) — galaxies: ISM — — X-rays: galaxies — X-rays: stars

1. INTRODUCTION

M31, the Andromeda Galaxy, is the closest spiral galaxy and belongs to the same spectral class as the Milky Way. It provides us with a sample of X-ray sources at a uniform and relatively nearby range ∼800 kpc (Stanek & Garnavich 1998). Galactic absorption in the direction of M31 is rather low (Stark et al. 1992), allowing the study of soft X-ray emission down to about 0.2 keV, which is not possible for the sources in the bulge or Galactic plane of our own Galaxy.

Observations with the Einstein and ROSAT satellites revealed the presence of multiple point X-ray sources within the galaxy, and also diffuse X-ray emission in the bulge

(Trinchieri & Fabbiano 1991, Primini, Forman & Jones 1993, Supper et al. 1997, hereafter Su97). The origin of the diffuse emission remains unknown. The possibilities include interstellar hot gas, or multiple faint point sources (stars or X-ray binaries) below the detection limit. Recently Irwin & Bregman (1999), hereafter IB99, reported that X-ray spectrum of M31 bulge has two components - hard and soft. They fitted together the data from the ROSAT PSPC and ASCA experiments. Trinchieri et al. (1999) confirmed the presence of two components in the spectrum of the bulge obtained with BeppoSAX. IB99 claim that the most likely origin for both components is the same, namely, the integrated emission from X-ray binaries. They, however, did not try to test this assumption directly from the study of spatially resolved spectra, but instead restricted themselves to indirect arguments.

In this paper we present results of our analysis of ROSAT PSPC data. For the first time we generated spatially resolved spectra of the bulge of M31. The results presented below demonstrate that the integrated spectrum of bright X-ray binaries is significantly harder than the spectrum of the diffuse X-ray emission in the bulge of M31.

2. OBSERVATIONS AND DATA REDUCTION

We analyzed the set of ROSAT PSPC observations discussed in detail by Su97. Description of the instrument can be found in Aschenbach et al. 1981, Pfeffermann & Briel 1982, Aschenbach 1988. We used all observations with a total exposure longer than 10,000 s that were taken before Oct 14, 1991[1]. (Table 1). Fig.1 shows the central part of M31 (observation RP600068N00). The angular resolution of ROSAT/PSPC does not allow a clean separation of point sources from the diffuse emission in the bulge of M31, because both are concentrated to the center of the galaxy. However, we still segregated these two components spatially as much as possible, collecting small regions around bright binaries into one spectrum, and photons from the areas without bright point-like sources into another. To identify point sources we used the ROSAT PSPC catalog published by Su97. To optimize the radius of photon collection for the point sources in the bulge, where diffuse emission is significant, we tried collection radii ranging from 30 to 60 arcsec for each source. As the radius increases we are collecting a great fraction of the source flux, but also an amount of diffuse contamination is increasing. We found that the choice of this radius does not change our conclusions described below. For X-ray binaries in the bulge, the typical

[1]different response matrix must be used with data collected after this date, hence it is not possible to sum spectra together with previous observations

radius was chosen to be 45 arcsec. Studying the integral spectrum of bright point sources outside of the bulge of M31, we collected all photons within 75 arcsec from each source.

We used only data within a central part of ROSAT's field of view, that is inside the central ring of PSPC support grid with ~ 20 arcmin radius. The background was measured in the same area of the detector over the regions without bright X-ray binaries. The same background spectrum was used with all spectra of observation RP600068N00, both for bright point sources, and for diffuse emission, except when diffuse emission was subtracted from point sources spectrum as a background (as discussed below). Various routines from the *ftools* package (v.5.0) were used to generate spectra and other necessary files, which were then used for spectral fitting with *xspec* (v.11.0) package. We ignored energy channels below 11 and above 219, and rebinned spectra so that each channel contained at least 25 counts.

3. SPECTRAL TEST RESULTS

To start we repeated the spectral analysis of IB99, using the integrated spectrum of bulge emission from inner 5 arcmin radius around the optical nucleus of M31 (see e.g. Crane, Dickel & Cowan 1992 for J2000 coordinates), including both point sources and diffuse emission. As IB99, we found that this spectrum cannot be satisfactorily described by single spectral component and requires two-component fit. We chose a combination of Raymond-Smith plasma emission and a power-law to represent the two spectral components, and obtained fit parameters consistent with IB99. However, the parameters of the fit are strongly correlated. There is the expected correlation between power law slope and absorption value, and also a correlation of power law slope with metallicity. This correlation is illustrated by Table 2. While IB99 used ASCA data to constrain a power-law slope, they left normalization of the spectrum as a free parameter. It is hardly possible to get reliable constraints from the joint fit of two different observations made by two different instruments in different time periods. It is especially so given the confirmed strong variability of individual sources within the bulge of M31 (e.g. Murray, Garcia & Primini 1999). We conclude that the fit parameters of the two-component model cannot be determined with good precision, and hence the contribution of soft and hard components cannot be measured well with the existing data.

We are nonetheless able to track the relative contributions of the two components, as a function of position, if we freeze the spectral parameters. In our following analysis we fixed the power law slope at 1.5, which was the best single power-law fit for M31 bulge for the joint ROSAT and ASCA spectrum (IB99). We also fixed the absorption column at the Galactic value $N_H = 6.73 \times 10^{20}$ cm^{-2} (Stark et al. 1992). These two parameters were fixed in all cases when two-component model have been used. It appears that in most cases a good fit is obtained with metallicity parameter of Raymond-Smith component fixed at 0.03. We allowed this parameter to be variable only when it was necessary to improve significantly χ^2 value. While the fit parameters presented in Table 3 depend on the model chosen, our main conclusion regarding the difference between the spectra of X-ray binaries and the diffuse emission is not model-dependent.

Using the model described above, we looked at the spectrum of the integral bulge emission (including all point sources) at various distances from the M31 center (less than 2 arcmin, between 2 and 5 arcmin, and between 5 and 8 arcmin). The contribution of the soft component decreased with distance from the center, in correlation with the decrease of the diffuse intensity in the image. The soft component fraction falls from 0.6 to 0.5 and then to 0.3, as we move from the inner 2 arcmin to the outermost annulus (Table 3).

For the next stage of our analysis, we separated bright point sources from diffuse component. Overall approach was to draw small circular regions around each point source listed in Su97. Then we integrated these regions into one spectrum ('XRBs'), and integrated the rest of the area into the second spectrum ('diffuse'). Admittedly, we cannot separate point sources and diffuse emission near the core completely by this method, because the density of diffuse emission is maximal near the core of M31, where the concentration of point sources is also maximal, however, relative contribution of both kinds of sources is different in spectra of those two types. In Table 3 we present two spectra for each type, which differ by the area where the emission was collected. We tried to collect diffuse emission from the area there its density corresponds to average density of the same emission around bright sources. It allowed us to subtract diffuse spectra from 'XRBs' spectra in an attempt to get 'clean' spectrum of point sources.

XRBs and diffuse emission near the core. For these spectra we extracted X-ray photons from the area near the center of M31, where the brightest point sources are concentrated and also the density of diffuse emission is maximal. The separation of two types of progenitors are especially challenging in this area. 14 bright point sources from Su97 catalog, which are located within 6 x 8 arcmin ellipse around the center of M31 (see Inset b of Fig.1) formed XRBs spectrum. Diffuse emission was collected over the ellipse 4 x 6 arcmin, but circles of 45 arcsec diameter around each catalogued source were extracted (Inset a of Fig.1). For 'XRBs near the core' the contribution of soft component is significant (0.50), but lower than for total emission from the same region (0.62). Soft component dominates the spectrum of diffuse emission collected in this area. If 'diffuse near the core' spectrum is subtracted from 'XRBs near the core', then soft component is no more significant in residual spectrum.

XRBs and diffuse emission in the bulge. Here we collected spectra of point sources and diffuse emission from larger area, where they are more easily separable. Spectra of 14 bright sources that lie within 8 arcmin from the center, but outside of central 2 arcmin, were integrated into 'XRBs in the bulge'(Inset c of Fig.1). Diffuse emission was collected from inner 5 arcmin, less 45 arcsec radii around all point sources listed in Su97 (see Inset d of Fig.1). Soft component is much stronger in the spectrum of diffuse emission (80% of total flux), than in the spectrum of XRBs (25% of total flux, not detected when spectrum of diffuse emission is subtracted).

We see that while all spectra can be satisfactorily fitted by the same model, the relative contribution of hard and soft component are significantly different for point sources and diffuse emission. Our spatially resolved analysis show that the spectrum of bright X-ray binaries in the bulge is different from the spectrum of diffuse component. Furthermore, it motivates us to suggest that hard component in the bulge spectrum is generated by X-ray binaries of the bulge, while the soft component originates from a diffuse source of different nature.

As an additional test for this assumption we analyzed the integrated spectrum of other X-ray binaries in M31. In this case we added together spectra of all bright point objects located outside of central 8 arcminutes. We did not add spectra of the sources marked as foreground stars or background galaxies in Su97. Altogether 61 bright point sources were added together to the spectrum labeled as 'XRBs in the disk' in Table 3. The integrated spectrum can be fit by single power-law component with a slope around 1.4 and absorption slightly higher than the Galactic value (Fig.3). No evidence for soft component was found. This spectrum is very close to the spectrum of 'XRBs in the bulge' with diffuse emission subtracted. We need to note that all spectra labeled as 'XRBs' in Table 3 include all bright compact sources in M31 and does not exclude supernova remnants or globular clusters. We suggest that a power-law spectrum with a slope of 1.3-1.5 is a more suitable template for the population of bright compact X-ray emitters, than the spectrum of the bulge of M31, which includes a significant soft component.

4. DISCUSSION

Our spatially resolved spectral analysis revealed a qualitative difference between the diffuse emission and the bright point sources in the bulge of M31. We have performed several tests and that gave consistent results. This is the first time that a spatially resolved spectral analysis of the M31 bulge was performed, and the two components of the bulge spectrum were separated spatially.

Previous studies were based on the spectrum of integral X-ray emission from the bulge, in comparison with spectra for individual sources. IB99 argued that low-mass X-ray binaries (LMXBs) may be responsible for both hard and soft X-ray components in the spectrum of M31 bulge. Here, we review their arguments against the results of our study.

First IB99 claimed that the contribution of the soft component to the integral spectrum of the bulge is significantly higher than the percent of unresolved diffuse emission detected with ROSAT (Primini et al. 1993). This argument suffers from at least two weaknesses. First, IB99 compare an absorption-corrected value for their spectral fit with *observed* (and hence absorbed) fraction of unresolved diffuse emission. Also, the relative strength of the spectral components is strongly model dependent, as demonstrated by our analysis (see Table 2). Hence, it is not surprising that the ratio of soft versus hard component measured by Trinchieri et al. (1999) with BeppoSAX differed from the results of IB99. The fraction of measured unresolved X-ray emission also varies significantly between ROSAT and Einstein (Trinchieri & Fabbiano 1991, Primini, Forman & Jones 1993). We do not believe that the comparison of two poorly determined values makes a strong argument. However, we would like to note that our analysis supports the conclusion of Primini et al. (1993) that the diffuse source near the center of M31 is either a new class of faint X-ray sources or a hot component of the interstellar medium.

As their strongest argument, IB99 suggest that the bright sources, faint sources and the total emission from the bulge all have similar spectra. This was based on the comparison of colors for the M31 bulge with individual sources. We show that in fact that the integral spectrum of the compact bright sources is significantly harder than the spectrum of diffuse emission in the bulge (see Fig.2 and Table 3). We cannot tell the nature of this diffuse source from ROSAT data alone. It may be an interstellar medium or perhaps the sum of multiple faint point sources. We have shown, however, that these faint point sources would then have much softer spectra and hence be of different nature from the bright ones. In fact, we favor the interstellar gas hypothesis, especially because an extended radio source of a similar size was also observed at the same position in M31 (Hjellming & Smarr 1982).

Corroboration for our conclusion comes from the analysis of the bright X-ray sources outside of the M31 bulge. Their integral spectrum does not show any hint for additional soft component. If one suggests that the bright compact X-ray sources in the bulge and outside it are of similar nature, then it is not surprising that spectrum of point sources in the bulge, after subtraction of diffuse component, is very similar to the spectrum of bright sources located outside of the bulge. We still cannot rule out completely the possibility that bright X-ray sources near the core of M31 belong to different population of X-ray sources and do have significant soft component in their spectra, however, our analysis does not provide any supporting evidence for such hypothesis.

The interpretation of these results goes far beyond the case of M31, because this galaxy, due to its proximity, often serves as a testbed for other early-type galaxies (see e.g. Irwin & Sarazin, 1998). X-ray spectra of many X-ray-faint galaxies had been found to be the sum of hard component and a very soft component, similar to the spectrum of the M31 bulge. Our analysis allows to suggest that the origin of this soft component is a hot interstellar gas, or some unknown population of faint, soft X-ray sources.

5. ACKNOWLEDGMENTS

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Table 1: Long Observations of M31 with PSPC/ROSAT.

Observation ID	Start Date	R.A.(2000) h m s	Dec.(2000) ° ' "	Exposure s
RP600064N00	15-Jul-91	00 41 02.40	+40 46 12.0	48,760
RP600065N00	24-Jul-91	00 46 48.00	+42 15 00.0	27,768
RP600066N00	25-Jul-91	00 45 21.60	+41 52 48.0	30,275
RP600067N00	26-Jul-91	00 43 55.20	+41 30 36.0	27,466
RP600068N00	27-Jul-91	00 42 28.80	+41 08 24.0	30,005
RP600079N00	14-Jul-91	00 39 36.00	+40 24 00.0	41,666

Table 2: Spectral fit parameters of $Raymond + PL$ model for the emission from the bulge of M31 (within 5 arcmin radius).

α_{pl}	kT_e, keV	$Z/Z_\odot$	N_H,$\times 10^{20}$ cm^{-2}	χ^2_ν(d.o.f.)	R$^a_{soft}$
1.0(fixed)	0.37	0.022	6.73(fixed)	1.24 (192)	0.69
1.0(fixed)	0.37	0.032	6.06	1.19 (191)	0.66
1.5(fixed)	0.33	0.029	6.73(fixed)	1.25 (192)	0.56
1.5(fixed)	0.30	0.69	4.38	1.21 (191)	0.33
2.0(fixed)	0.32	0.067	6.73(fixed)	1.28 (192)	0.31
2.0(fixed)	0.31	0.88	5.84	1.18 (191)	0.20

[a] – fraction of soft component in total unabsorbed model flux in 0.2-2.0 keV band

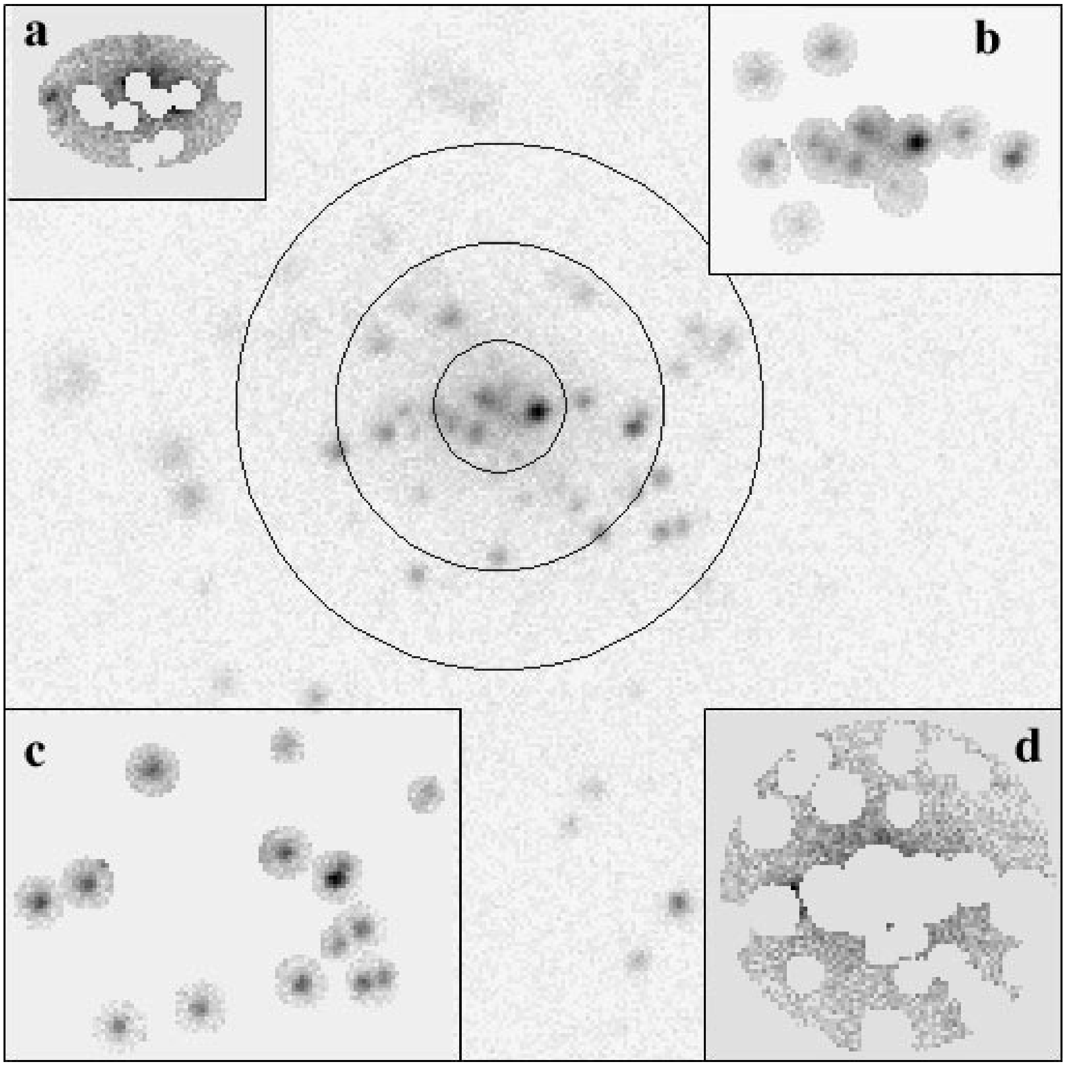

Fig. 1.— Central part of M31 observed with ROSAT/PSPC. Concentric circles are drawn at 2, 5 and 8 arcmin radia from the center. *Inset a:* Diffuse emission within 4x6 arcminute ellipse after the subtraction of bright point sources (see 'diffuse near the core' spectrum in Table 3). *Inset b:* Bright point sources in the central part of M31 ('XRBs near the core'). *Inset c:* Bright point sources in the annulus between 2 and 8 arc from the center ('XRBs in the bulge'). *Inset d:* Diffuse emission within 5 arcmin from the center after the subtraction of bright point sources ('diffuse in the bulge').

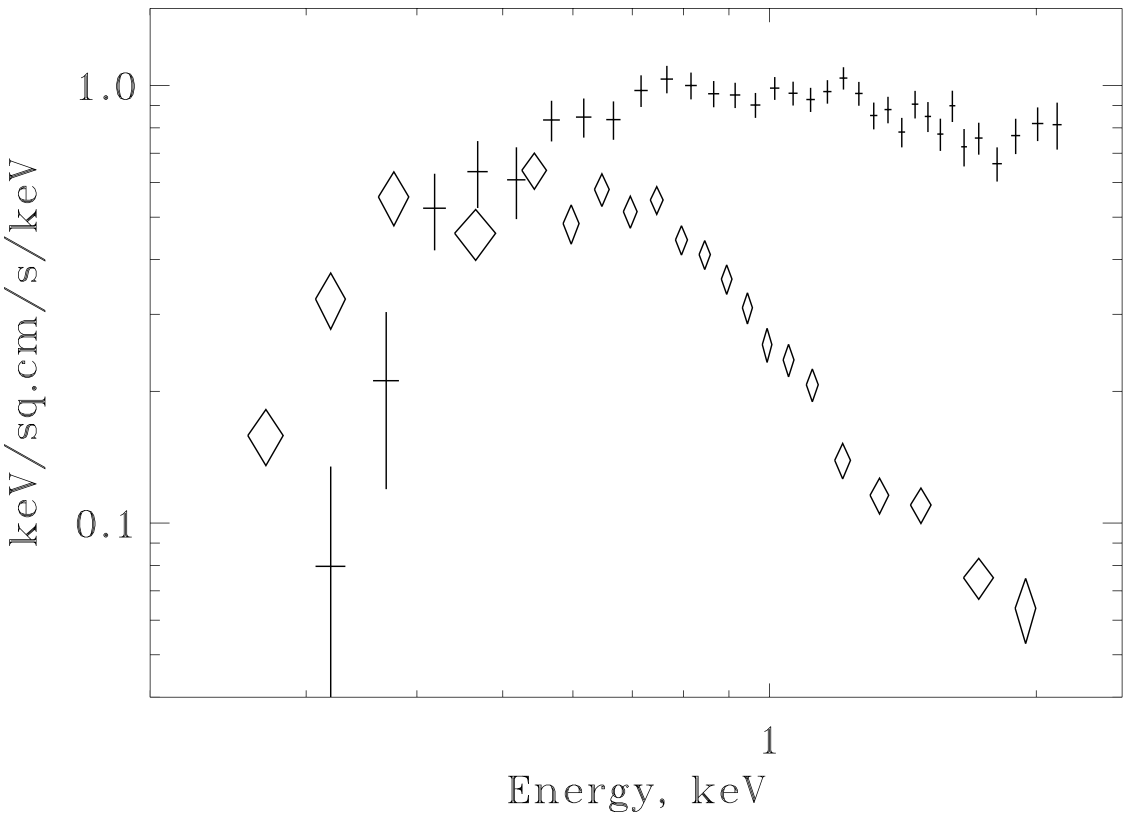

Fig. 2.— Distribution of the energy in the spectra of the diffuse emission near the core and bright point sources in the bulge of M31. *Diamonds* shows the spectrum of diffuse component after the removal of bright point sources from the image ('diffuse near the core' in Table 3). *Crosses* represent the spectrum of 'XRBs in the bulge' after subtraction of diffuse component ('diffuse in the bulge' in Table 3). Total emission from the bulge of M31 is a sum of both types of spectra.

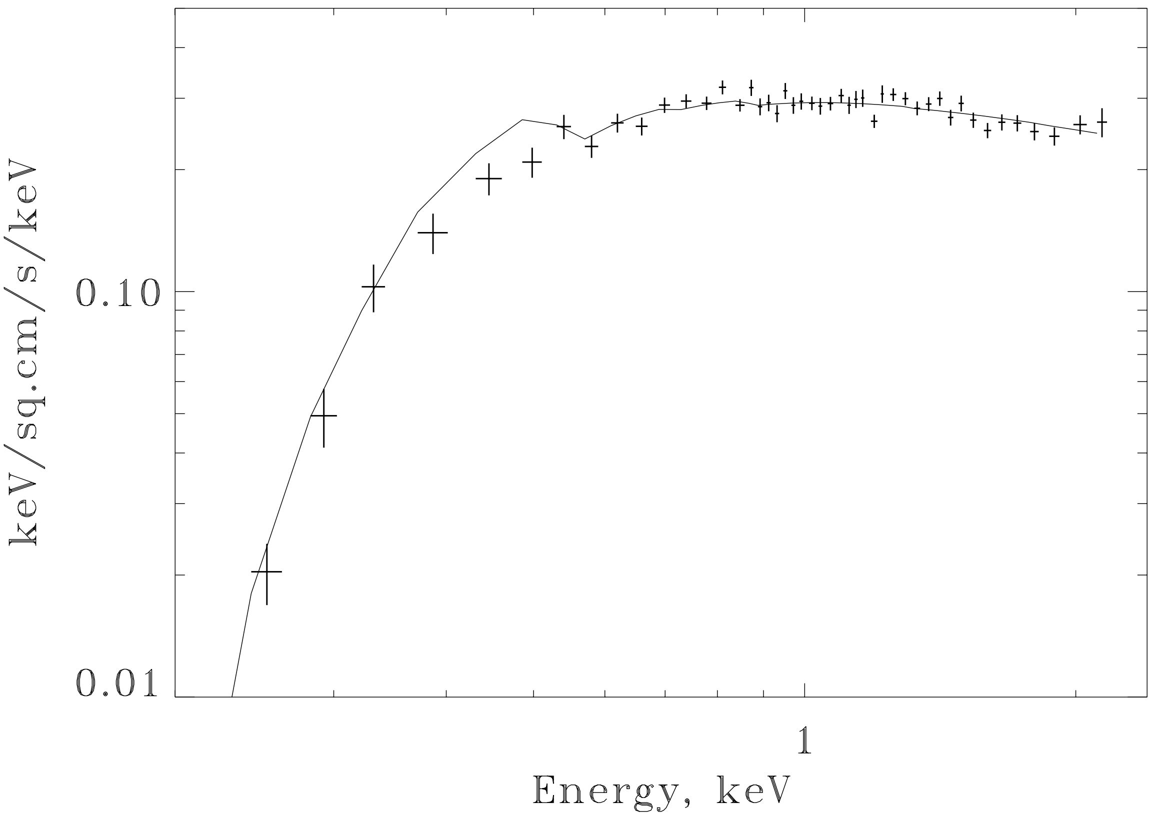

Fig. 3.— Summed energy spectrum of 61 bright X-ray sources in the disk and halo of M31. Solid line is best fit power law with photon index α=1.43 and absorption N_H=7.3$\times 10^{20}$ cm^{-2}.

Table 3: Best-fit parameters for different regions of M31.

region	α_{pl}	kT_e, keV	$Z/Z_\odot$	N_H,$\times 10^{20}$ cm^{-2}	χ^2_ν(d.o.f.)	F^a_{tot}	R^b_{soft}
inner 2 arcmin	1.5(fixed)	0.35 ± 0.02	0.03(fixed)	6.73(fixed)	1.21 (172)	10.6	0.61
ellipse 6x8 arcmin	1.5(fixed)	0.32 ± 0.02	0.03(fixed)	6.73(fixed)	1.25 (184)	16.3	0.62
2-5 arcmin ring	1.5(fixed)	0.32 ± 0.02	0.03(fixed)	6.73(fixed)	1.08 (180)	10.5	0.50
5-8 arcmin ring	1.5(fixed)	0.34 ± 0.06	$0.10^{+0.5}_{-0.07}$	6.73(fixed)	1.04 (164)	3.95	0.30
XRBs near the core	1.5(fixed)	0.37 ± 0.02	0.03(fixed)	6.73(fixed)	0.92 (185)	13.6	0.50
XRBs near the core^c	1.49 ± 0.07	-	-	6.73(fixed)	0.62 (186)	5.28	0.
XRBs in the bulge	1.5(fixed)	0.58 ± 0.11	0.03(fixed)	6.73(fixed)	0.98 (175)	6.44	0.25
XRBs in the bulge^c	1.31 ± 0.05	-	-	6.73(fixed)	1.14 (176)	4.36	0.0
XRBs in the disk	1.43 ± 0.04	-	-	7.3 ± 0.4	1.29 (86)	2.18	0.0
diffuse near the core	1.5(fixed)	0.31 ± 0.01	0.03(fixed)	6.73(fixed)	1.06 (141)	5.76	0.77
diffuse in the bulge	1.5(fixed)	0.31 ± 0.02	0.03(fixed)	6.73(fixed)	1.25 (129)	3.98	0.80

^{a} – total unabsorbed model flux in 0.2-2 keV band, in units of 10^{-12} ergs s^{-1} cm^{-2}

^{b} – fraction of soft component in total unabsorbed model flux in 0.2-2 keV band

^{c} – in this case the spectrum of diffuse emission has been taken as a background